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REFOCUSING PROPERTIES OF PERIODIC MAGNETIC FIELDS

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16. Abstract

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SUMMARY

The use of depressed collectors for the efficient collection of spent beams from linear-beam microwave tubes depends on a refocusing procedure in which the space charge forces and transverse velocity components are reduced. This study evaluates the refocusing properties of permanent magnet configurations whose axial fields are approximated by constant plateaus or linearly varying fields. The results provide design criteria and show that the refocusing properties can be determined from the plateau fields alone.

INTRODUCTION

An electron beam emerging from a traveling wave tube or from a klystron is in a severely nonlaminar (turbulent) state. That is, the trajectory paths of its particles (streamlines) cross each other. The efficient collection by means of a depressed collector of the spent electrons from a linear-beam tube depends on preparing the beam advantageously before injection into the collector. This beam processing is called refocusing and its purpose is twofold:

(1) Dilution of space charge forces.

(2) Reduction of transverse velocity components.

The reduction of transverse velocity components can be regarded as a partial recovery of beam laminarity.

At any station the average angle and the rms deviation from the average can be computed from the trajectories of the particles. The rms deviation is a measure of beam turbulence. A beam with zero rms angular deviation would be laminar and such a beam would be easier to collect.

In this report the definition of a successfully refocused beam will be taken as one in which

(1) The final beam radius is larger than its initial radius (diffusion of space charge)

(2) The final average angle is near zero (i. e., the beam is nearly paraxial)

(3) The final rms angular deviation is less than its initial value (the beam becomes less turbulent)

A method of collecting electrons with an electrostatic multistage depressed collector and the procedure of magnetic refocusing was suggested by Kosmahl (ref. 1) and successfully demonstrated on a 12-gigahertz traveling wave tube (ref. 2). Subsequent work on refocusing includes that of Branch and Neugebauer (ref. 3), Tammaru (ref. 4), and Stankiewicz (ref. 5). These studies were concerned principally with the refocusing properties of magnetic fields that are produced by solenoids. However, for space applications the use of permanent magnets has an advantage in both weight and reliability. In this study only magnetic configurations which simulate circuits with permanent magnets are considered. Such magnetic circuits have regions of field reversal and have the look of periodic magnetic fields.

The purpose of this study is to give design criteria for the refocusing of beams that are characteristic of traveling wave tubes. No attempt is made to design a universal refocuser. It is improbable that any single design could be used to refocus electrons having widely different energies, at least not in the restricted lengths that are required in microwave tubes. There are, however, some general concepts that can be used to design refocusers. The application of these concepts will be demonstrated for a specific distribution of particles.

MODEL, ASSUMPTIONS, AND INITIAL CONDITIONS

Figure 1 shows a magnetic circuit of the type studied in this report. The integral of the magnetic field along the entire axis will vanish; that is, the average axial field over the length of the refocuser will be zero.

Because it was anticipated that a large number of configurations would have to be studied in order to design an optimum refocuser, it was decided to approximate the axial fields with linearly varying and zero gradient fields. This has the advantage that the paraxial fields are equal to the axial field and no additional calculation is necessary. This can be shown by means of the axial expansion formula used in axisymmetric potential problems (see, for example, ref. 6).

The axial expansion formula could be used to find the paraxial fields for any function on the axis providing all of its derivatives are known. But this is no guarantee that such a configuration could be physically constructed. The correct analytical method of finding the paraxial fields is to numerically solve for the magnetic potential from Laplace's equation over a given geometry. Then, unless the change in magnetic configuration is simply a change in scale, one must solve again for the magnetic potential for each geometry. However, this report will be helpful in deciding which configurations are promising. The principal assumptions made in this study are the following:

(1) Axisymmetry. This idealization is desirable in the manufacture of linear beam microwave tubes and departures from axisymmetry are regarded as undesirable. Mathematically this assumption means the problem is two-dimensional in (r, z) coordinates. (Symbols are defined in appendix A.)

(2) Axial space charge forces. Axial space charge forces are due to the bunching of electrons. The emergent beam becomes debunched within a few tunnel radii after leaving the rf interaction region. Therefore, the axial space charge can be ignored.

(3) Beam composition. The beam is assumed to be an ensemble of beamlets which interact only through the action of the cumulative space charge potential. Each beamlet moves as though the entire charge of the beam were concentrated on the axis. By Gauss' law this potential will have a logarithmic dependence on r.

(4) Initial conditions. Electron beams in traveling wave tubes are formed with almost Brillouin flow conditions (i.e., cathode flux of less than 10 percent of the confining field flux). The cathode flux has the effect of adding a constant amount of angular momentum to the beam. Because of the assumed axisymmetry, the angle coordinate is a cyclic variable and the angular momentum is a constant of the motion and should be conserved. However, for a real tube, the argument is proposed that, because of slight asymmetries in the tube and because of the turbulence of the exit beam, it is highly unlikely that such an orderly motion should persist. It seems more probable that, at the exit, the beam will have no memory of cathode conditions. Therefore, the 32-particle distribution is completely specified at the inlet to the refocuser by 96 initial conditions or three initial conditions per particle. These are the initial radius, axial velocity, and radial velocity. The initial conditions were generated by an existing computer program for a helix traveling wave tube (TWT). It is assumed that the output velocities from this program represent fairly typical TWT outputs. However, the predicted initial radii were changed so that the average radius is about one Brillouin radius. This represents a much higher than usual space charge compression for a TWT and a more difficult refocusing problem. It is felt that if adequate refocusing can be demonstrated for the high compression beam the results will certainly be valid for beams of lesser compression.

(5) Statistical parameters. It is assumed that the average beam radius, the average angle with respect to the axis, and the rms deviation of final angles provide an adequate description of the important beam properties in designing a collector.

The ideal beam leaving the refocusing region would be one in which the injection angles into the collector increase monotonically with decreasing axial energy and in which most of the beam energy is in the axial kinetic mode. This energy sorting requirement is based on numerous computer experiments using the programs developed by Reese (ref. 7). Such a beam would have undergone a radial expansion; it would be paraxial and it would have a small rms deviation of final angles. That is, the statistical parameters used in this report define a minimal set of beam properties with which to describe a refocused beam. However, in lieu of actual experimental measurements the proper precollector beam preparation remains speculative.

METHOD OF SOLUTION

The equations of motion are derived in appendix B. A Runge-Kutta integration routine is used to solve these equations numerically. At certain axial stations (ζ = constant) along the magnetic configuration the angle α is computed for each particle, that is,

$$\alpha = \arctan\left(\frac{P_\rho}{P_\zeta}\right) \tag{1}$$

where (P_ρ, P_ζ) is the radial and axial momenta normalized to the dc momentum.

The average angle $\langle\alpha\rangle$ and the rms deviation $\sigma(\alpha)$ is computed from

$$\langle\alpha\rangle = \frac{1}{N}\sum_{i=1}^{N} \alpha_i \tag{2}$$

and

$$\sigma(\alpha) = \left\langle(\alpha - \langle\alpha\rangle)^2\right\rangle^{1/2} \tag{3}$$

or

$$\sigma^2(\alpha) = \frac{1}{N}\sum_{i=1}^{N} (\alpha_i - \langle\alpha\rangle)^2 \tag{4}$$

where $N = 32$.

The radial and axial coordinates (ρ, ζ) are normalized to the Brillouin radius and the magnetic fields are normalized to the Brillouin field.

The integration begins at the tube exit at a point that coincides with the vanishing of the confining magnetic field. This is defined as the origin of the refocusing section ($\zeta = 0$).

From the origin, the magnetic field increases linearly until a predetermined plateau is reached. The slope of the linearly rising field was chosen as 0.2 (unit Brillouin field per unit Brillouin radius) and the same slope is used throughout the configuration whenever the field changes. It will become evident in the next section that the choice of slope is a minor consideration compared to the choice of plateau. The rest of the configuration proceeds as in figure 1 with the first plateau followed by a linear change to a second plateau of negative field (i. e., the field vector in the negative direction) and a final linear decay to zero field. The absolute value of the area under each lobe must be the same.

The simultaneous vanishing of the average angle and the minimization of the rms deviation may require more than two lobes (one permanent magnet). In the design that is presented later in this report it was necessary to add another two lobes (another permanent magnet). The second magnet has the effect of lowering the average angle while keeping the rms deviation nearly constant. The absolute value of the areas under these two lobes are kept equal.

RESULTS

The energy in a beam (see eq. (B1)) is shared in two kinetic modes (axial and radial velocities) and in one potential mode (average beam radius). Three useful observations based on the conservation of energy and on the computed results have been made concerning the behavior of turbulent beams in magnetic fields; they are the following:

(1) An expanding beam entering a region of increasing magnetic flux will be decelerated axially with a consequent increase in turbulence. The radial kinetic energy is increasing and $\sigma(\alpha)$ will also increase.

(2) An expanding beam entering a region of decreasing magnetic flux will be accelerated axially with a consequent decrease in turbulence. The increase in axial velocity is proportional to the square of the radius and to the gradient of the magnetic field (see equations of motion, eq. (B10)). The energy will be transferred from the radial kinetic mode to the axial kinetic mode and this will decrease $\sigma(\alpha)$.

(3) A beam in a region of constant magnetic flux will conserve its axial energy. The beam undergoes an oscillatory motion in which the energy is transferred between radial kinetic and radial potential modes. Then $\sigma(\alpha)$ will be periodic and will exhibit a minimum value. The periodicity of $\sigma(\alpha)$ is a function of the phases of the particles upon entering the region of constant magnetic flux.

Figure 2 shows the effect of subjecting the beam to a decelerating magnetic field followed by a plateau. Plotted in this figure is the rms deviation $\sigma(\alpha)$ as a function of axial distance ζ with the magnitude of the plateau field as a parameter. In this configuration the magnetic field rises linearly (slope = 0. 2) to the plateau field value indicated in the figure.

The interesting features of these curves are the minimums that occur for plateau values below 0.55. The dashed line is the locus of minimums and the dotted line represents the beam expansion into a region of zero magnetic field (free expansion). Because the initial rise of the curves are all coincident with the free expansion curve it is clear that this stage of beam expansion is nearly independent of the applied external field. And the subsequent behavior of the beam in the plateau field is of more importance than how the plateau value was reached.

The location of the minimums along the axis gives a design point for the plateau length at which the magnetic field should begin to decay. If the decay point is placed beyond the minimums, a rapid increase in $\sigma(\alpha)$ will be experienced as shown in the figure.

Figure 3 is a plot of the locus of minimums as a function of plateau magnetic field. Numerous computer cases indicate that this curve is independent of the previous history of the expansion (i.e., acceleration, deceleration, or prior field traversal). This figure seems to show a finite asymptotic value to $\sigma(\alpha)$ at $B = 0$. Linear extrapolation gives a value of 0.75°. The numerical integration for $B < 0.1$ requires too much computer time and the minimums below $B = 0.1$ were, therefore, not found. For the high fields, the curve has a terminus where the minimums degenerate into inflection points (see fig. 2).

Figure 3 is the most important result of this study. It gives a prescription for designing a refocuser and it also indicates the limiting value to $\sigma(\alpha)$ that could be attained with a given configuration.

Consider first a refocuser composed of a series of magnetic field step functions whose lengths are determined from the location of $\sigma(\alpha)$-minimum values. Figure 3 indicates that the magnitude of each step must always decrease if some recovery of laminarity is to be attained at every stage. The theoretical limit to $\sigma(\alpha)$ (if the last step function had a magnitude of 0.1) would be 1.7°. (It is assumed that the electrostatic collector begins where the magnetic field vanishes. In reality, however, there is an axial drift space of 2 or 3 Brillouin radii in which a free expansion occurs. This residual expansion improves the velocity sorting.) Because overall length is an important consideration in refocuser design and because low magnitude fields require longer lengths in which to affect the beam, we will never consider fields less than 0.1.

Consider next the more realistic case in which the transition from one magnetic plateau to another takes place in a finite length (finite slope) and that the plateaus alternate in sign. Each transition region then subjects the beam to an acceleration and a subsequent deceleration. The situation is shown in figure 4 for a case in which the first plateau has a magnitude of 0.4 and a cutoff is located at $\zeta = 5.1$ (from fig. 2).

The second plateau has the various values indicated on the figure and the dotted line is the locus of minimums. The accel-decel region and its effect on $\sigma(\alpha)$ is clearly shown in this figure. The second plateau will further decrease $\sigma(\alpha)$ because the initial value of $\sigma(\alpha)$ on entering the region of constant field is larger than the value indicated by the locus of minimums for the cases considered. If the second plateau had a value of -0.35, the beam would experience an increase of $\sigma(\alpha)$. In figure 4 the magnetic field averaged over the length of the configuration is equal to zero. This is in keeping with the restriction that configurations must be attainable with permanent magnets.

It is noted that, except for the final acceleration of the beam as the field decays to zero, the entire effect on $\sigma(\alpha)$ is again determined only by the plateau fields. Because of the requirement that the plateau fields decrease in magnitude as the beam traverses the refocuser, the average radius of the beam will be larger than the initial radius and there will be a diffusion of space charge.

So far only two of the criteria for refocusing have been discussed. It is also necessary to ensure that the beam entering the collector be approximately paraxial with system and not diverging and converging rapidly. Figure 5 shows the behavior of the average angle $\langle\alpha\rangle$ in the same configurations and for the same conditions as in figure 4. Comparison of these two figures shows that the refocusing is somewhat unsatisfactory. At this point it would probably be best to regard the results as a good preliminary guide to the construction of a refocuser. Experience shows that a magnetic configuration in which the fields change smoothly has much better refocusing properties than one with discontinuous derivatives.

However, for purposes of illustration, it is interesting to carry on the design to include two more lobes of a magnetic field configuration.

The final result shown in figure 6 satisfies all the minimal refocusing requirements. It should be noted that finite angles of 1° to 3° are perfectly suited for high collector efficiency. Particles that enter the collector region with angles equal to zero on the axis are uncollectable and are detrimental to high efficiency.

The results provide an explanation for the large number of successful refocusing configurations that were found in reference 5. The solenoidal fields in that study always accelerated the beam into a constant plateau field. The present study shows that this will always decrease $\sigma(\alpha)$ and expand the average beam radius. Successful refocusing in reference 5 was, therefore, synonomous with reducing the average beam angle to a small angle.

The results also provide an insight into the difficulty one has in launching a beam with perfect Brillouin initial conditions. Such a beam traverses a region of increasing magnetic flux and experiences an axial deceleration. If the beam is not perfectly laminar (e.g., due to thermal effects), the decelerating field will amplify the nonlaminarity.

CONCLUSIONS

This report evaluates the refocusing properties of magnetic field configurations that simulate circuits containing permanent magnets. The simulation is first order, that is, the fields are approximated with constant plateau fields and linearly varying fields.

One of the purposes of refocusing is to reduce the degree of turbulence of the spent beam. A measure of the turbulence is the rms deviation of the particles' trajectory angles from the average beam angle. For a given plateau field, the results show that this parameter has a unique minimum value which is independent of the previous history of the beam. The results lead to the following conclusions:

1. The initial stage of beam expansion is a function of internal beam parameters rather than applied fields. Therefore, the refocuser design must be regarded as specific rather than general. The refocuser must be tailored to the beam.

2. The existence of unique minimums of beam turbulence for a given plateau field provides design points. Therefore, the refocusing properties can be determined from the plateau fields alone.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 10, 1975,
506-20.

APPENDIX A

SYMBOLS

B	magnetic field
B_o	Brillouin field, used as normalizing field
B_z	z-component of magnetic field
B_ζ	normalized z-component of magnetic field
b	Brillouin radius, defined in appendix B
e	electron charge
H	Hamiltonian function
I_o	dc current
m	particle mass
(P_r, P_z)	momenta conjugate to cylindrical coordinates
(P_ρ, P_ζ)	normalized momenta conjugate to normalized cylindrical coordinates
(r, z, φ)	cylindrical coordinates
t	time variable
u_o	dc velocity
V	electrostatic potential
α	particle angle defined in eq. (1)
ϵ_o	vacuum dielectric constant
θ	normalized time variable
(ρ, ζ)	normalized cylindrical coordinates
σ	rms angular deviation defined in eq. (3)
ψ	magnetic flux density
ω_c	cyclotron frequency, eB/m

APPENDIX B

EQUATIONS OF MOTION

It was shown in reference 5 that the Hamiltonian for a particle with a charge to mass ratio $-e/m$ moving in an external axisymmetric magnetic field and under the influence of a cumulative space charge potential V can be written as

$$H = \frac{1}{2m}\left(P_r^2 + P_z^2\right) + \frac{1}{2m}\left(\frac{e\psi}{2\pi r}\right)^2 - eV \tag{B1}$$

where (P_r, P_z) are the conjugate momenta to the cylindrical coordinates (r, z) and ψ is the magnetic flux through a circle of radius r normal to the axis z. Thus,

$$\psi = \int_0^r \int_0^{2\pi} B_z r\, dr\, d\varphi = \pi r^2 B_z \tag{B2}$$

The integration in equation (B2) can be completed because of axisymmetry and because B_z on the axis will be limited to constants or to linear functions of z (see ref. 5). Therefore, B_z is not a function of r or φ.

The space charge potential will be taken as

$$V = \frac{I_o}{2\pi\epsilon_o u_o} \ln r \tag{B3}$$

where I_o and u_o are the dc beam current and velocity, respectively. Equation (B3) assumes that the particle is located on the edge of the beam and, hence, sees all of the charge as being on the axis. Properly speaking equation (B3) is the potential of an idealized beamlet with no z-component of space charge force. The beam is then composed of an ensemble of beamlets.

The equilibrium of Brillouin radius b is defined by the condition

$$\frac{\partial H}{\partial r} = 0; \qquad r = b; \qquad B_z = B_o \tag{B4}$$

Carrying out the differentiation of equation (B1) results in

$$\frac{B^2 B_d^2}{4m} b - \frac{eI_o}{2\pi\epsilon_o u_o} \frac{1}{b} = 0 \tag{B5}$$

or

$$b = \left(\frac{2mI_o}{\pi\epsilon_o u_o e B_o^2} \right)^{1/2} \tag{B6}$$

If the variables are normalized by letting

$$\left.\begin{aligned} r &= b_\rho \\ z &= b\zeta \\ P_r &= (mb\omega_c)P_\rho \\ P_z &= (mb\omega_c)P_\zeta \\ t &= \frac{1}{\omega_c}\theta \\ B_z &= B_o B_\zeta \end{aligned}\right\} \tag{B7}$$

where $\omega_c = (e/m)B_o$ and $(\rho, \zeta, P_\rho, P_\zeta, \theta)$ are the normalized versions of (r, z, P_r, P_z, t), the Hamiltonian can then be written (to within a constant) as

$$H = \left(\frac{e^2 B_o^2 b^2}{m} \right) \left\{ \frac{1}{2} \left(P_\rho^2 + P_\zeta^2 \right) + \frac{1}{8} (\rho B_\zeta)^2 - \frac{1}{4} \ln \rho \right\} \tag{B8}$$

We will redefine the scaled Hamiltonian (without changing nomenclature) as

$$H = \frac{1}{2} \left(P_\rho^2 + P_\zeta^2 \right) + \frac{1}{8} (\rho B_\zeta)^2 - \frac{1}{4} \ln \rho \tag{B9}$$

The equations of motion are

$$\left.\begin{aligned}
\frac{d\rho}{d\theta} &= \frac{\partial H}{\partial P_\rho} = P_\rho \\
\frac{d\zeta}{d\theta} &= \frac{\partial H}{\partial P_\zeta} = P_\zeta \\
\frac{dP_\rho}{d\theta} &= -\frac{\partial H}{\partial \rho} = \frac{1}{4\rho}\left[1 - (\rho B_\zeta)^2\right] \\
\frac{dP_\zeta}{d\theta} &= -\frac{\partial H}{\partial \zeta} = -\frac{1}{4}\rho^2 B_\zeta \frac{dB_\zeta}{d\zeta}
\end{aligned}\right\} \qquad \text{(B10)}$$

These equations were numerically solved by means of a fourth-order Runge-Kutta integration routine for each of the 32 particles and the appropriate initial conditions.

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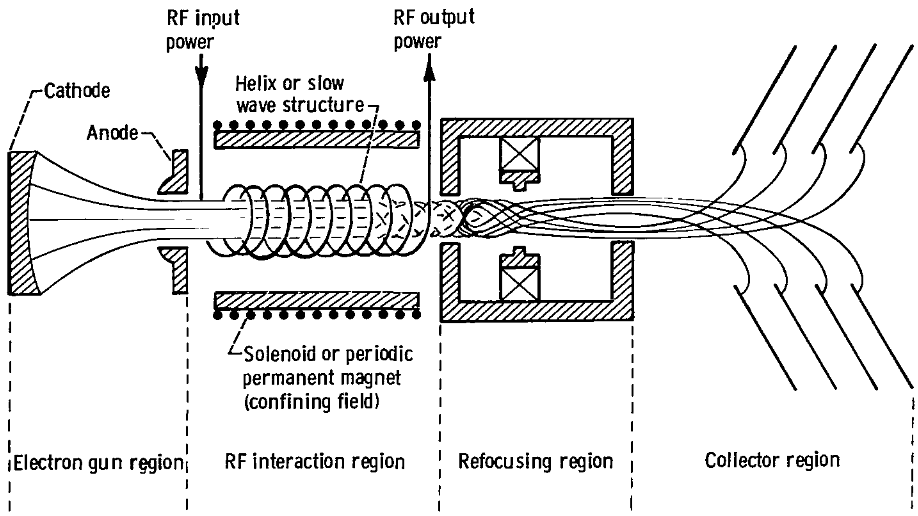
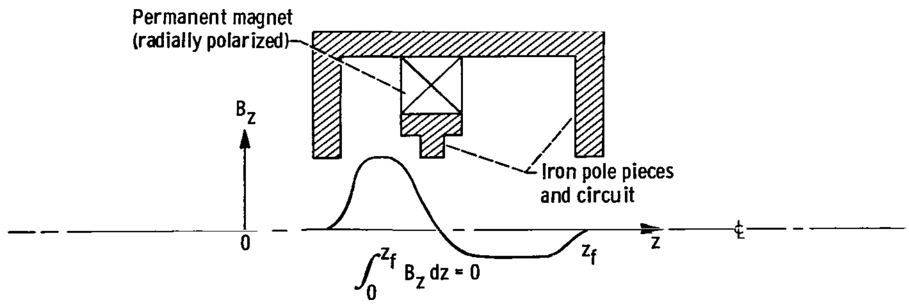


(a) Traveling wave tube with refocuser and collector.



(b) Detail of refocusing region.

Figure 1. - Schematic drawing of traveling wave tube with detailed refocusing region.

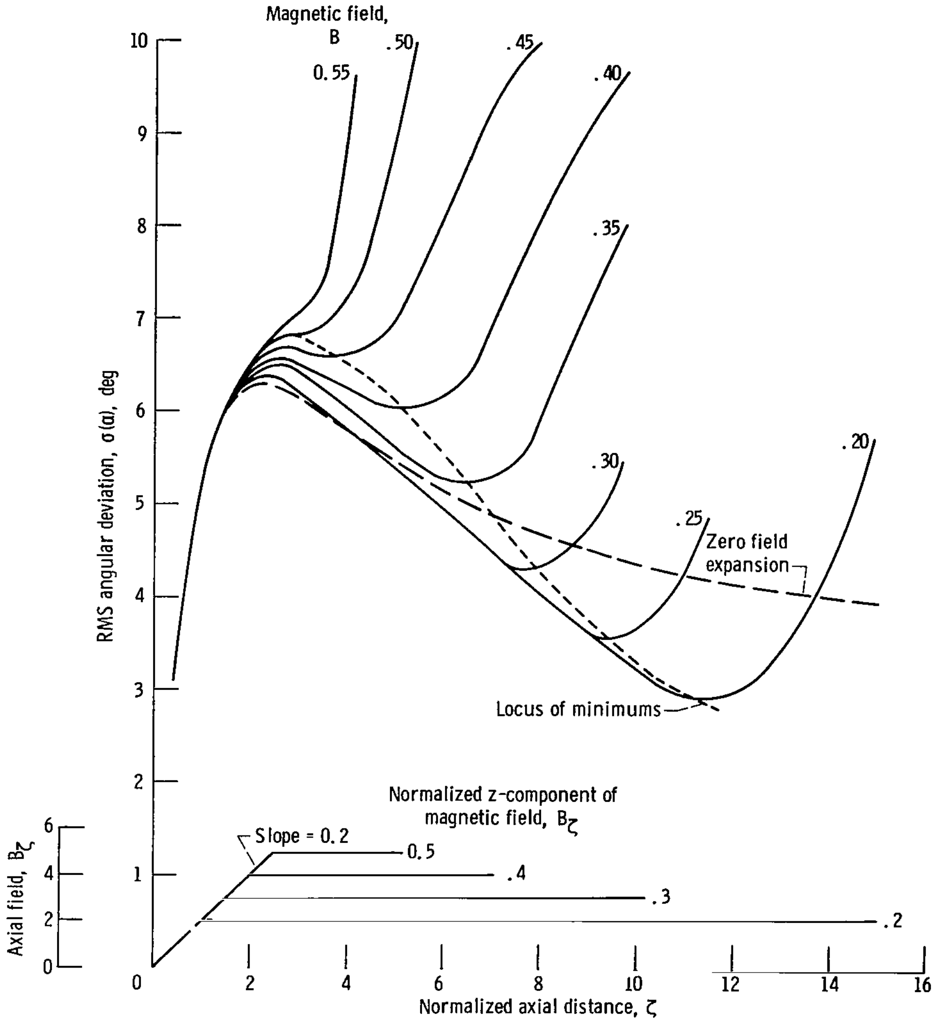


Figure 2. - Effect of decelerating field followed by plateau field.

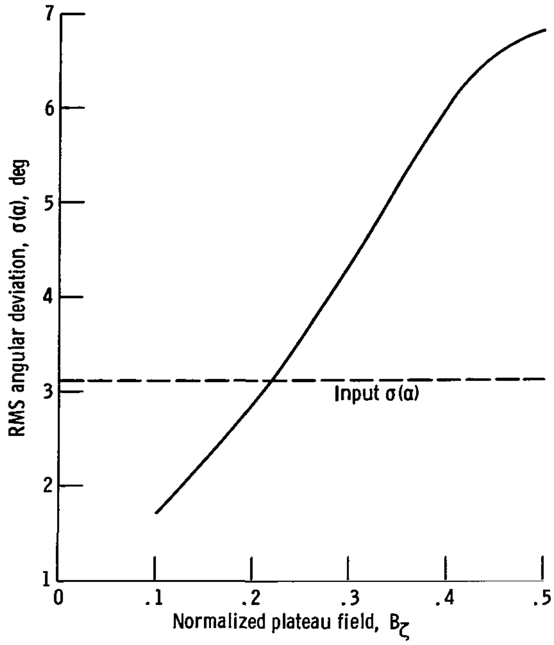


Figure 3. - Locus of minimum rms angular deviations as a function of plateau field.

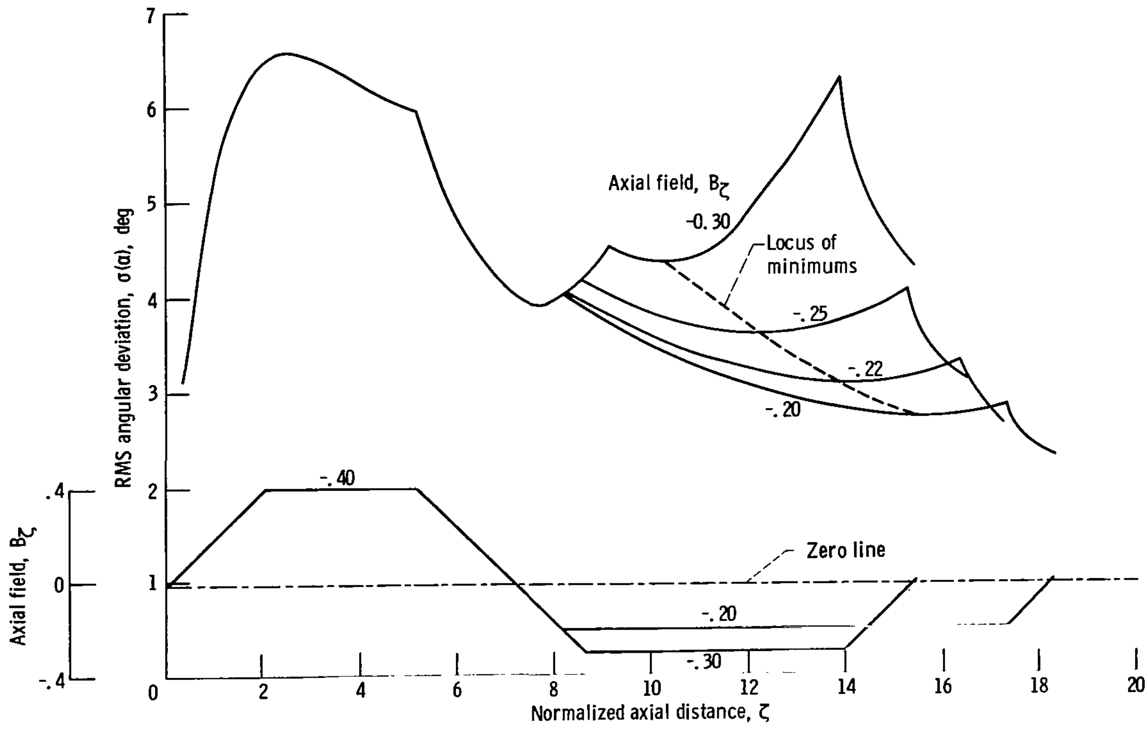


Figure 4. - RMS angular deviation as a function of axial distance for a magnetic field configuration simulating a permanent magnet circuit (see fig. 1).

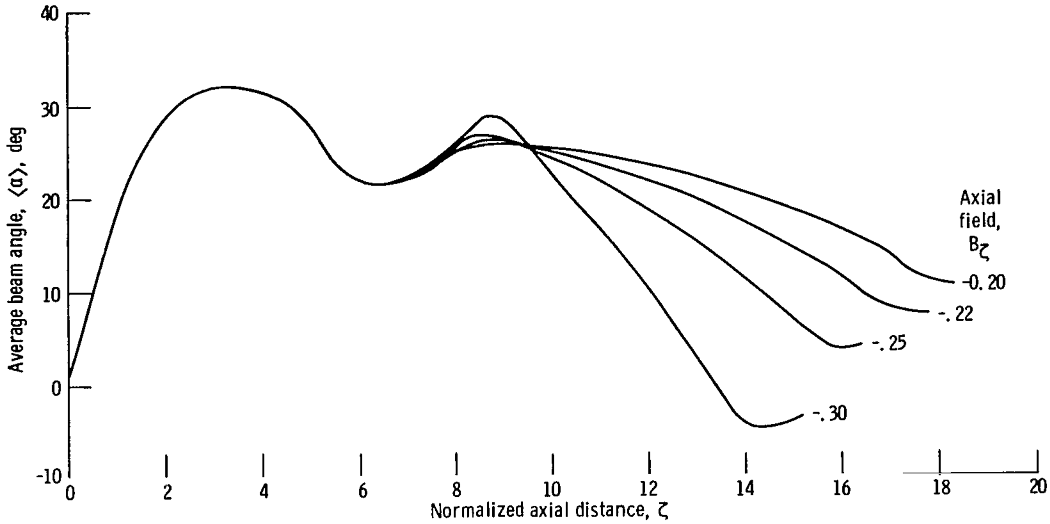


Figure 5. - Behavior of average beam angle in magnetic configurations simulating permanent magnet circuits (refer to figs. 1 and 4).

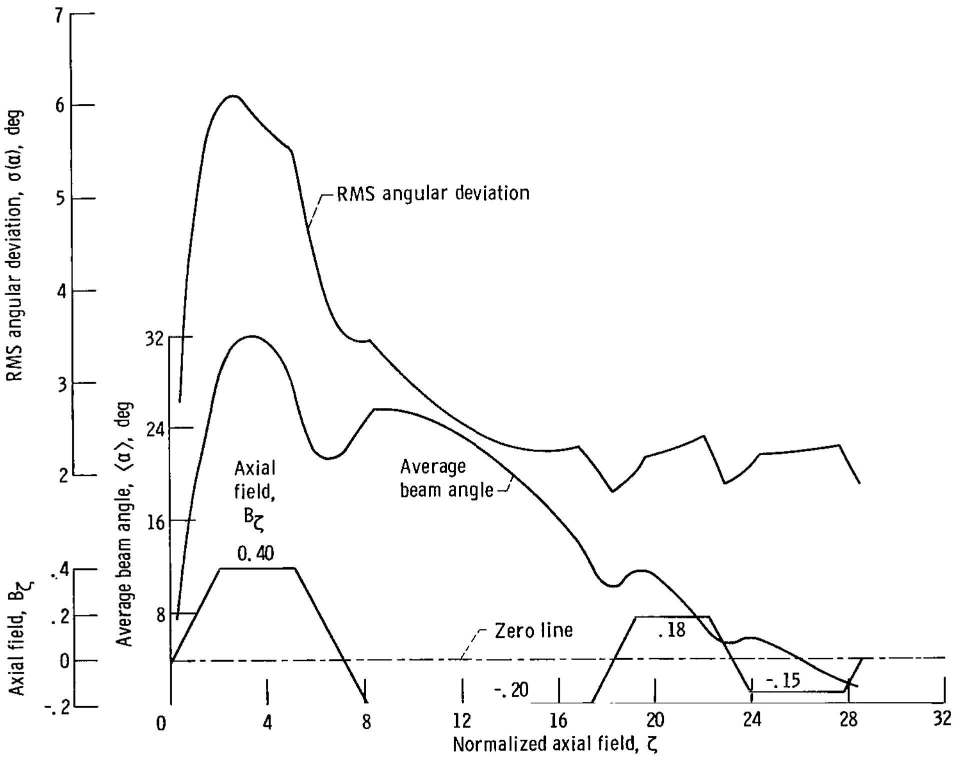


Figure 6. - Effect of second permanent magnet.

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